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AUTHOR Champagne, Audrey B.; And Others
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ABSTRACT

Based on the premise that the problems students experience when learning physics derive in part from their own firmly embedded naive theories, this report offers an instructional approach which takes into account the information that students bring to instruction. Specific attention is given to problems associated with the learning of mechanics. A review is provided of the research that focuses on the theories of motion held by students who have experienced no formal mechanics instruction along with research that demonstrates how this knowledge affects students interpretation of instruction. Results from research are then applied to the formulation of cognitive objectives for introductory mechanics instruction. Several instructional strategies are offered to facilitate the students attainment of the proposed objectives. Descriptions are also provided on how the constructs of concepts, propositions, and schemata are used to describe declarative knowledge about the motion of objects typically used by uninstructed students and by experts and novice physicists. A list of references is included. (ML)

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INSTRUCTIONAL CONSEQUENCES OF STUDENTS' KNOWLEDGE ABOUT PHYSICAL PHENOMENA

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AUDREY B. CHAMPAGNE, RICHARD F. GUNSTONE, AND LEOPOLD E. KLOPFER

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Audrey B. Champagne, Richard F. Gunstone, and Leopold E. Klopfer

Learning Research and Development Center
University of Pittsburgh

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INTRODUCTION

There is general agreement among physics instructors and students that mechanics is difficult to teach and to learn (Kolody, 1977). Students have difficulty comprehending classical mechanics, and physics instructors often express disappointment with the outcome of their efforts to instruct students in classical mechanics. This instructional problem has been discussed at length in the literature of physics education where various underlying causal factors contributing to the problem have been suggested (Gerson & Primrose, 1977; Halley & Eaton, 1975; Hudson & McIntire, 1977).

In addition to identifying possible reasons for the apparent opacity of physics, and especially mechanics, science educators have attempted various resolutions of the difficulty. Variables that may contribute to students' success in learning physics that have been investigated include (1) mathematical skills, (2) general level of cognitive development, and (3) specific cognitive processes (e.g., Arons, 1976; Renner, Grant, & Sutherland, 1978). The basic strategy used by science educators to investigate these variables is to identify a single student characteristic (level of cognitive development as defined by Piagetian theory, for example) and demonstrate that the characteristic is correlated with success in physics. Then, typically, instruction is modified to take into account student inadequacies with respect to this characteristic, and studies are conducted to demonstrate that student achievement improves. However, this research strategy has produced limited results, as Mallinson (1977), Peterson (1979), and other commentators have pointed out.

A factor contributing to students' difficulties in learning mechanics, in the view of some physicists, philosophers of physics, and, more recently, science

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educators and cognitive psychologists, is that students come to introductory physics courses with firmly embedded theories of how and why objects move. These naive theories have some characteristics in common with an Aristotelian view of the world.[1] Dijksterhuis (1969) notes that historically a great effort was necessary to outgrow the Aristotelian view of motion and that

> to this day every student of elementary physics has to struggle with the same errors and misconceptions which then had to be overcome, and on a reduced scale, in the teaching of this branch of knowledge in schools, history repeats itself every year. The reason is obvious: Aristotle merely formulated the most commonplace experiences in the matter of motion as universal scientific propositions, whereas classical mechanics, with its principle of inertia and its proportionality of force and acceleration, makes assertions which not only are never confirmed by everyday experience, but whose direct experimental verification is fundamentally impossible . . . (p. 30)

These and other writings by physicists, physics educators, and philosophers of science describe a situation in which certain features of students' pre-instructional knowledge of the subject matter domain is in clear conflict with the canonical view of the subject matter domain which students will be required to learn. This suggests that the problems students experience when learning mechanics derive, in part, from the disparity between their experience-based knowledge about the motion of objects and the facts, principles, and theories of Newtonian mechanics.

In this chapter, we propose an approach to the instructional problem posed by mechanics which takes into account information about the motion of objects that students bring to instruction. We review research that provides descriptions of the facts, principles, and theories of motion held by students who have experienced no formal mechanics instruction, along with research that demonstrates how this knowledge affects students' interpretations of instruction. Results from research contrasting the physics knowledge of expert physicists and novices (individuals who have completed one or two college level physics courses) are used to formulate cognitive objectives for introductory mechanics instruction. Finally, we propose several instructional strategies to facilitate the students' attainment of the objectives. We hypothesize that these strategies will measurably alter the extent, accuracy,

[1]Aristotle considered rest to be the natural state of objects. In the absence of any cause, an object does not move; conversely, when an object is moving, its motion must have been caused, usually by a force. Aristotle also argued that the *speed* of an object is directly proportional to the force acting on it, and inversely proportional to the resistance of the medium through which the object is moving. In Newtonian physics, it is stated that an object will continue in its existing state (either ar rest or moving with constant speed in a straight line) unless it is acted on by a *net* force. The *acceleration* of the object is directly proportional to this net force, and inversely proportional to the mass of the object.

and structural organization of the students' knowledge, thus bringing it into a state closer to that of expert physicists.

As we noted, previous approaches focused attention on the generalized thinking and mathematical skills the student brings to instruction. The approach we propose emphasizes the significance of the domain-specific declarative knowledge—facts (for example, the acceleration due to gravity at sea level is 9.8 m/s^2), concepts (acceleration), propositions (acceleration is proportional to net force) and theories (motion occurs only when a force is exerted[2])—that the student brings to instruction.

Two important features of declarative knowledge are elements and structural organization. Elements or structural units of declarative knowledge include concepts, propositions, and schemata. The characteristics of these constructs are not well-specified. Concepts and the relations among them are often represented in node-link diagrams (Anderson, 1983). Two concepts and the relationship between them comprise a proposition. Schemata are larger structural units and are used when representing declarative knowledge about classes of things or events. A playground slide, a stairway, a wedge, and a hill are objects. A child sliding down the slide, a girl walking up the stairway, the wedge splitting a piece of wood, and an elephant sliding down the hill are physical events. A physicist, when thinking as a physicist, conceives of the class of things in this example as inclined planes and the class of physical events as objects moving along inclined planes. This knowledge is represented as schemata—a schema for inclined planes and a schema for objects moving along inclined planes. Schemata have slots. For a specific instance, the slots are filled by information unique to that instance. In the instance of a red metal playground slide, the plane slot is filled by the information red and metal, and the inclined slot is filled by the information that the angle between the plane and the horizontal is about 45 degrees.

The constructs of concepts, propositions, and schemata are used in this paper to describe declarative knowledge about the motion of objects typically used by uninstructed students and by expert and novice physicists.

THE UNINSTRUCTED STUDENTS' EXPERIENCE-DERIVED KNOWLEDGE

Results from empirical studies provide detailed descriptions of uninstructed students' declarative knowledge about the motion of objects. The findings from this research consistently demonstrate that prior to formal mechanics instruction most young people (and uninstructed adults) have a

[2]This is an example of an experience-based theory observed in most untutored children and adults. The theory stands in direct contradiction to formal physical theory.

conception of motion that is more Aristotelian than Newtonian (Champagne, Klopfer, & Gunstone, 1982; Champagne, Klopfer, Solomon, & Cahn, 1980; Driver, 1973; Driver & Easley, 1978; Leboutet-Barrell, 1976; Singer & Benassi, 1981). Our conclusion that the pre-instructional concepts are Aristotelian is based on data collected using several demonstrate, observe, and explain (DOE) tasks.

The DOE tasks have three parts: (1) some simple physical apparatus and a manipulation of it are described; (2) the students are asked (a) to predict the outcome of the demonstration and (b) to report the information they used to generate the prediction; (3) the demonstration is then done and the students are asked to describe their observations and to discuss any conflicts between their predictions and their observations.

Our contention that students' conceptions influence their understanding and remembrance of science texts and lectures, their observations, and their interpretations of their observations is also based on observations made during and after administration of the DOE tasks. In one DOE task used in our investigations, students are asked to compare the times for two objects to fall equal distances. The objects are the same shape and size but differ in mass. This task has been administered to several groups of academically talented adolescents (seventh and eighth graders) and to beginning college physics students.

An example from the students' protocols illustrates the interactions between the students' conception of the speeds of falling objects and their interpretation of information obtained from text or lecture. A significant number of the college and middle-school students predict that the heavier object will fall faster and justify the prediction by stating that Galileo proved the general principle that heavier objects fall faster. To support their assertion, students describe an experiment that they recall having learned that Galileo performed—dropping a feather and a gold coin. The students note that Galileo reported that the coin falls faster, thus arguing that Galileo proved that heavier objects fall faster. We infer this to mean that the students have been exposed to some of Galileo's work, either by reading or hearing about it. However, if we compare the generally accepted account of Galileo's argument with the students' interpretation, we note significant differences. Galileo used a thought experiment to support his assertion that when air resistance is controlled for, the heavier object and the lighter object will fall at the same rate. Galileo's complete argument is that if a feather and a coin are dropped in air, the coin will fall faster; if, however, the objects are dropped in a vacuum, the effects of the upward push of the air will no longer be present and both objects will be observed to fall at the same rate. It is our observation that students who predict that heavier objects fall faster remember the part of Galileo's experiment that is consistent with their concep-

tion of falling objects and forget the part of the experiment that is inconsistent with their conception.

There is also evidence that students' observations tend to be consistent with their predictions. There are protocols in which students' observations are clearly in conflict with prediction. In these cases, students often hedge in their observations. For example, one student predicted that the heavier object would fall faster and wrote in his observations that indeed the heavier one had fallen faster but expressed surprise that the speeds were so nearly the same.

Our observations of middle-school students, immediately after the administration of the DOE task with the two falling objects and during the eight weeks of instruction that followed, support the hypothesis that the students' interpretations of science experiments are influenced by their beliefs about the relationships between an object's mass and its speed in free fall. When the administration of the task was completed, one group of students was told that they could experiment on their own with the equipment used in the demonstrations. Several students did so. One student weighed the two blocks. He had predicted that the metal block would fall faster than the plastic block, but his observations contradicted his prediction based on the belief that heavier objects fall faster. To resolve this contradiction, he reasoned that, despite the difference in the materials from which the two blocks were made, they must be the same weight because they fell at the same rate. He proceeded to test this hypothesis by weighing the two blocks.

Two other students (Tammy and Mary) who also predicted that the heavier object would fall faster, experimented by dropping the blocks from a greater distance above the floor than the demonstrator had dropped them from. Tammy climbed onto a table and dropped the blocks while Mary put her head on the floor to hear when they struck the floor. These students reasoned that the blocks had, in fact, fallen at different rates, but that the difference in descent times was too small to be observed over the short distance (approximately one meter) used in the original demonstration. They tested this hypothesis by designing an experiment which used a more sensitive procedure (i.e., dropping the blocks from a greater height) to illuminate any difference in the blocks' rates of fall.

The observations in the DOE task with two falling objects of different mass continued to be questioned by the students throughout the eight weeks of instruction. Some of the students continued to argue that they failed to observe differences in the rates of fall because of the insensitivity of the experimental procedure. Their experiments were designed to demonstrate differences in the rate of free fall. This was to be accomplished by increasing the sensitivity of the experimental procedures by increasing the distance through which the objects dropped. They also placed their heads on the floor

and either sighted along the floor or listened for the impact in order to better distinguish between times of impact. It must be remembered that these experiments, far from being idle exercises for the students, reflected a real dilemma that they faced. The students' Aristotle-like conceptions that the greater downward force applied to the heavier object implies that its speed of fall must be greater are incompatible with the observation that the objects fall at the same rate. One way to resolve this dilemma is to design experiments which will discredit that observation. A discredited observation does not act as a challenge to the students' pre-instructional conceptions, which they are reluctant to change anyway.

These observations are consistent with findings emerging from cognitive psychology that demonstrates the impact of existing knowledge in memory on the comprehension of text (Anderson, Reynolds, Schallert, & Goetz, 1977; Bransford & McCarrell, 1974; Lindsay & Norman, 1972). Early studies in the area of reading comprehension aimed at demonstrating that something other than the linguistic structure of a sentence is required to explain a person's comprehension of that sentence. The "something other" is described as the person's world knowledge and often is characterized as a "schema," "plan," or "script." Bransford and McCarrell (1974) review studies which indicate that the process of understanding text involves creation of "semantic descriptions" that use both the reader's world knowledge and the sentence input. Anderson, Reynolds, Schallert, & Goetz, (1977) indicate that an individual's "private" representation of the world can affect text comprehension. In general, studies of text comprehension indicate the facilitative effect of schemata or world knowledge. However, studies of science learning, reviewed by Driver and Easley (1978), indicate that world knowledge may be logically antagonistic to science content and may persist after science instruction.

Research we have conducted (Champagne, Klopfer, & Anderson, 1980) is consistent with the Driver and Easley results. Our work illustrates that the belief that heavier objects fall faster than lighter objects is not easily changed by instruction, thus demonstrating the strong influence that prior knowledge has on the effectiveness of instruction—in this case, the prior knowledge has an inhibiting effect on learning. In a study of beginning college physics students, about four students in five asserted that, all other things being equal, heavier objects fall faster than lighter ones. These results were particularly surprising since about 70% of the students in the sample had studied high school physics, some for two years. A chi-square test showed that students in the sample who had studied high school physics did not give significantly different responses from those who had not. In a report of a similar study of the knowledge of gravity possessed by beginning first-year physics students at Monash University, all of whom had successfully completed two years of high school physics, Gunstone and White (1981) con-

clude: (1) "students know a lot of physics but do not relate it to the everyday world"; and (2) "In many instances, the students used mathematical equations to explain predictions, though often inappropriately, which indicates that they had lots of physics knowledge to hand but were unskilled in seeing which bit applied to the given situation" (p. 299). In their discussion, Gunstone and White note that, not only has the students' pre-instructional general knowledge of the world been insufficiently integrated with their school physics knowledge, but the pre-existing declarative knowledge continues to dominate their explanations of physical phenomena even after instruction.

Characteristics of the declarative knowledge of beginning physics students have been compiled from the analysis of empirical studies investigating students' pre-instructional conceptions of the causes of motion of objects. These characteristics include

1. Concepts are poorly differentiated. Terms used in classical mechanics are used in everyday life—terms such as acceleration, momentum, speed, and force. The meanings of these terms as used by physicists are quite different from the way in which thay are used in everyday life. Thus, we observe that students misunderstand physics instruction because they interpret their physics lectures and texts in the context of their real-world definitions of the terms. For example, students use the term speed, velocity and acceleration interchangeably; the typical student does not perceive any difference between two propostions such as these: (a) The speed of an object is proportional to the [net] force on the object; (b) The acceleration of an object is proportional to the [net] force on the object.

2. Propositions are imprecise. This imprecision derives from at least three different sources. (a) Some of the imprecision of propostions is attributable to the meanings students have for technical concepts wich are different from the canonical meaning. Example: More force means more speed. (b) Other imprecision can be interpreted as errors of scale (Gunstone & White, 1981). Example: Gravity pulls harder on objects that are closer to the earth. (This propostion, in the context of an object falling a distance of three meters, is correct only in theory because the different in the force of gravity (approximately a part in 10^{13}) is too small to measure. If, however, the difference in distance from earth were large (several hundred kiometers), the difference in the force of gravity is significant.) (c) Other propostions are just wrong and may arise because of students' attempts to inappropriately formulate general rules of motion from their experiences in the real world. Example: Heavy objects fall faster than lighter objects.

3. Explanatory schemata are situation-specific, suggesting that there is no naive abstract representation extant in the schemata that makes the schemata applicable to large number of physical situations. In our work with

middle-school students, we have observed that they fail to notice that a proposition which they have used to explain motion in one situation is directly contradicted by a proposition they use to explain motion in another situation. This suggests that the students are unaware of any need for consistency across situations. For example, students do not recognize that the same physical laws apply to objects in free fall and to objects sliding down an inclined plane.

The research reviewed here has enabled us to develop a description of uninstructed students' declarative knowledge about the motion of objects. We now turn to research that provides descriptions of the declarative knowledge of expert physicists and novices. Having these descriptions, we can then compare the experts' and uninstructed students' knowledge states and derive specifications of the changes that instruction should promote.

The Physics Knowledge of Expert Physicists and Novices

Much of the information about the physics knowledge of expert physicists and novices has been obtained from the analysis of thinking-aloud protocols obtained as individuals solve physics problems. The work of Chi, Feltovich, and Glaser (1981) is an example of this approach.

In summarizing the several experiments in their study, Chi *et al.* conclude that the following differences characterize the knowledge that expert and novice physicists apply in the solution of physics problems:

1. The problem-type schemata of experts are based on physical principles (for example, energy conservation and Newton's second law) and those of novices are based on physical objects (for example, springs and inclined planes) and constructs (for example, friction and gravity.
2. The contents of the schemata of experts and novices do not differ significantly in information content; however, the novices' structures lack important relations, specifically, relations between the surface features of the problem and the scientific principles which are the basis for solutions.
3. Links exist between the experts' abstract representation of features of the problems and the physical principles which are the basis for the solution of the problem. These links do not exist in novices.
4. Experts' schemata are arranged hierarchically along the dimension of abstractness; in contrast, the different levels of the novices' knowledge are not well integrated, thus preventing easy access from one level of abstraction to another.

SUMMARY

Significant differences in knowledge exist about motion possessed by the uninstructed person, the novice, and the expert physicist (Champagne, Gunstone, & Klopfer, 1982). The differences associated with the quantity, accuracy, abstractness, and structure of the information has important implications for learning and instruction. The differences help explain observed difficulties students have in learning mechanics and provide useful information for the design of instruction.

Empirically derived descriptions of the characteristics of the knowledge of the motion of objects of uninstructed students, novices, and experts are summarized in Table 5.1. Although this summary table cannot display all the nuances associated with the knowledge, it does make evident the contrasts and similarities in the characteristics of the three groups' knowledge with respect to principles, surface features, and second-order features, each of which is briefly explained in the first column. The second column in the table describes current conceptions of the characteristics of physics knowledge of the uninstructed students. The fourth column describes characteristics of the experts' declarative knowledge. By comparing the characteristics of the uninstructed students' and experts' knowledge, the nature of the needed changes in the students' knowledge can be specified.

It should be emphasized that, when the instructional strategies we shall propose are employed, we do *not* expect the students' knowledge to pass through a transition stage showing all the characteristics of the novices' schemata described in the third column of Table 5.1. Specifically, our proposed instructional strategies will encourage the reconciliation and integration of the uninstructed students' existing knowledge developed from real-world experiences with the knowledge developed as a result of formal physics instruction. Thus, the creation of the conflicting knowledge observed in many novices is avoided.

COGNITIVE OBJECTIVES AND STRATEGIES FOR MECHANICS INSTRUCTION

One way of conceiving of the objectives of instruction is in terms of changes which will transform students' existing knowledge into an approximation of the knowledge of experts. By contrasting specific features in the knowledge states of experts and uninstructed students (and sometimes of novices), we can derive cognitive objectives to be attained by the student with respect to those features.

Table 5.2 summarizes essential differences in the declarative knowledge of the three groups and the instructional objectives for mechanics instruction

TABLE 5.1 Domain-Specific Knowledge of Uninstructed Students, Novices, and Expert Physicists

Features	Characteristics of Unstructured Student's Knowledge	Characteristics of Novice's Knowledge	Characteristics of Expert's Knowledge
Principles Ideas of some degree of generality that express relationships; principles are applied to solving problems; can serve to organize schemata.	Principles are generalized rules derived from everyday experiences (world knowledge). They are imprecise propositions. The imprecision is due to vagueness about the meaning of concepts, errors of scale, and inappropriate formulations of general rules. The principles (rules) have limited scale and tend to be situation-specific. The notion that an abstract principle can apply to a range of different physical situations is lacking or poorly developed. There appears to be no awareness of the need for consistency among the rules that cover different physical situations.	Principles are relationships between physical variables expressed as equations or rules. Some of the principles are the major physical laws expressed in equation form, but there is no evidence that they serve as organizers of schemata.	Principles are major physical laws, which are highly abstract and express relationships of great generality. Included with each principle are the conditions under which the principle applies. Principles have associated schemata, which are oriented by the content and applicability conditions of the principle. The applicability conditions usually are expressed in terms of second-order features.
Objects and Physical Conditions (Surface Features) Physical objects and conditions described or presented in a problem situation; physical features of objects and their states of motion or position that are directly perceivable from verbal description; diagrams or direct observation of the physical situation.	Concrete objects and the directly observable properties of objects are present. A reasonable inference is that the objects and properties define the specific physical situation which, in turn, directs the search in memory for a general rule that covers it.	Physical objects and their surface features are the basis for categorizing problems. It is inferred that an object or a configuration of objects functions as the organizing element (node) in its schema for the problem. The content of the representations may be concrete objects or abstractions at the level of diagrams.	Concrete objects, their physical configurations, and diagrams of objects are present in the schemata, but none of these is prominent. It is inferred that objects serve primarily as vehicles for identifying second-order features, and that sometimes they trigger the activation of a particular principle based schema.
Physics Concepts and Symbols (Second-Order Features) Idealizations of physical objects (e.g., an elephant is represented as a point mass) and constructs or entities (e.g., energy, force), conventional representations of physical entities (e.g., vector components).	There is no evidence that second-order features are represented in these schemata. Concepts and terms are present, but many are poorly differentiated. The meanings of the terms are their real-world meanings, rather than their technical meanings in physics.	Some conventional representations of physical entities are present, and idealizations of physical objects may be used in problem representations. Concepts and terms related to the objects which dominate the problem-solution schema are present. Novices report taking terms directly from the problem statement to identify equations that could be approximately employed in solving the problem.	Representations of physical objects in their idealized form are prominent, with the content of the representations determined by the organizing schema. Physical entities are represented according to the conventions of the field. Some experts report that features abstracted from problem statements help to select the basic approach to problem solutions, thus indicating direct links between these second-order features and principles. Concepts relevant to the organizing schema are present. Associated with each concept are its interconnections of relationships with other concepts and with the schema's major physical law.

TABLE 5.2 Contrasting Features in Declarative Knowledge and Their Related Instructional Objectives and Strategies

Contrasting Features in Declarative Knowledge States of Unstructured Students (U), Novices (N), and Experts (E)	Instructional Objectives Derived from the Contrasts	Instructional Strategies to Facilitate Attainment of Instructional Objectives
CONCEPT MEANING Meanings attributed to technical terms by U differ in significant ways from the meanings of E and N. Example: U: acceleration means speeding up. E and N: acceleration means a change in the magnitude or direction of velocity.	Students know both the everyday meaning and the canonical definition of mechanics and can specify differences between the everyday and canonical meanings.	*Interactive dialogue using multiple instances.* Provides students with opportunities to become aware of the meanings they attribute to physical concepts, how these meanings differ from concept to concept. Examples: (1) doing physics problems or describing a physical event to a friend, or (2) doing mechanics problems in which there is no motion. Dialogue provides students with opportunities to contrast their meanings of concepts with those of the physicists.
CONCEPT DIFFERENTIATION U do not differentiate mechanics concepts. Example: U: weight and mass are the same thing. N and E: mass and weight are perfectly correlated but distinct.	In analyzing a given physical situation, students can explain which of two poorly differentiated concepts is the relevant concept to apply.	*Interactive dialogue using multiple representations.* Provides students with opportunities to verbalize their analysis of physical situations in a way that simply substituting 9 g for mass (m) or 45 dynes for weight (F) in an equation does not. We hypothesize that the verbalization will help differentiate weight (a force) expressed in dynes from mass expressed in grams.
PROPOSITIONS IN SCHEMATA U - presence in schema of incorrect propositions. Example: motion implies force. N - presence in schema of conflicting propositions which are applied in different situations. Example: Motion implies force proposition applied in the analysis of real-world situations. Change in motion implies force proposition applied in the quantitative solution of physics problems. E - propositions present in schema are internally consistent and widely applicable. Example: Change of motion implies force proposition is applied in analyzing all pertinent problems.	Students apply change in motion implies force proposition in real-world situations. Students contrast implications of the difference in the two relationships between force and motion expressed by the propositions: (1) Motion implies force, and (2) Change in motion implies force.	*Ideational confrontation.* Provides opportunity for students to (1) be explicit about the propositions they assume in invoking the presence of forces in physical situation (For example, U generally invokes forces only in situations where there is motion.) and (2) make explicit the relationship between motion and force in the propositions they use.
STRUCTURAL FEATURES Concept integration of U and N is sparse, with fewer links among concepts than for E. Example: N - experientially derived motion-of-objects schema is not integrated, or reconciled with Newtonian mechanics schema. Integration of representations in U and N is poor, while they are well integrated in E. Example: N - representations of surface features of physical situations are poorly integrated with abstract representations of physical situations; these, in turn, are poorly integrated with propositions which link canonical objects and physical constructs used in abstract representations. E - representations of surface features of physical situations are integrated both with abstract representations of physical situations and with propositions linking the canonical objects and constructs of abstract representations.	Students qualitatively analyze mechanics problems. (1) Produce an abstract representation of a physical situation. (2) Recognize that situations with very different surface features can have the same abstract representation. (For an example, see Appendix A where the situations of 8 problems have the same abstract representation.) (3) Recognize that the problems can be solved by the application of the same mechanics principle.	*Qualitative analysis of problems to change structural features of mechanics schema.* Forges links between the physical situation, its abstract representation using canonical objects and mechanics constructs, and the principles (Newton's second law, $F = ma$) which link properties of the canonical objects and constructs. Also forges links between concepts (e.g., between mass and weight) to integrate them better, thereby contributing to concept differentiation.

based on those differences. These objectives specify features of the ideal state which the learner will approximate but do not detail how far the learner will move along the continuum from beginning student to expert as a result of a particular course or sequence of instruction. Further refinement of the objectives for a certain instructional sequence must take into account many other factors, including the content the instruction will cover, the time available for instruction, and the age and academic aptitude of the students for whom the instruction is intended. Also included in Table 5.2 are instructional strategies proposed to achieve the objectives.

The process of specifying instructional strategies based on differences in declarative knowledge is more complex than that of objectives specification. The process requires the analysis of traditional formal physics instruction, informal educational experiences, and everyday experiences with moving objects—in short, analysis of the many situations that affect the development of knowledge about the motion of objects. Based on available information concerning differences in the experiences of the three groups (uninstructed students, novices, and experts), it is possible to hypothesize how differences in experiences produce the observed differences in declarative knowledge. This process is informed by theory and the results of empirical studies investigating the relationship between experience (usually formal instruction) and cognitive change.

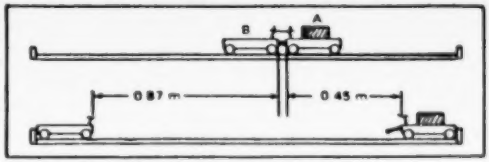
The following example relates differences in declarative knowledge with differences in experiences. The three groups of interest differ with respect to (1) the quantity and extent of formal mechanics instruction, (2) experience in solving mechanics problems, and (3) the extent of their verbal interactions about mechanics. The studies by Chi et al. (1981) suggest that the contents of novices' declarative knowledge pertinent to particular types of physics problems are similar to those of experts with respect to objects, concepts, and terms; however, experts' knowledge structures contain many more linkages. (It is important to this discussion to note that the more extensive information base, which experts have acquired as a result of their greater exposure to formal instruction, is not necessary for and indeed does not seem to be called upon in the successful solution of problems of the type on which the analysis of expert-novice differences is based.) The observation that novices' cognitive contents resemble those of experts is an indication that the didactic method of instruction is effective for imparting discrete bits of information. However, the detailed analysis of problem-solving behaviors of novices suggests that the structural organization of the information resulting from exposure to didactic instruction is less than satisfactory. This suggests an important limit on the effectiveness of didactic instruction. We hypothesize that the multiple *links* between the contents of experts' knowledge struc-

tures and their more abstract schemata develop, in part, from extensive practice in problem solving. Cognitive theory suggests that the development of highly integrated, abstract declarative knowledge structures may be facilitated by verbal interactions with others about mechanics.

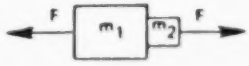
A significant difference between the physics experience of experts and novices is that experts have had greater opportunities for communicating about physics with other people. This suggests that verbal interaction may have an effect on building the desired links between the contents of students' knowledge structures that parallels the effect of extensive practice in problem solving. In theoretical support of this notion, Anderson (1977) has suggested that one type of verbal interaction, namely, Socratic dialogue, is a possible mechanism for producing schema change. We proposed several instructional strategies that involve dialogues to bring about the students' attainment of the kinds of objectives identified in Table 5.2. Although student-student and student-teacher dialogues are the common denominator in these strategies, we distinguish several dialogue strategy varieties on the basis of differences in instructional procedures, in the stimulus materials used, and in the instructional objectives which the strategies are designed to further. Four of these dialogue-based strategies represented by the strategies in the rightmost column of Table 5.2 are interactive dialogues using multiple instances, interactive dialogues using multiple representations, ideational confrontation, and qualitative analysis of problems. We shall describe and illustrate each of these instructional strategies.

Interactive Dialogues Using Multiple Instances

This strategy is conceived to facilitate development of (1) physics problems schemata and (2) correct physical meanings of physics terms. An illustration of the procedures of the multiple instances strategy follows. The students first are presented with a set of five or more mechanics problems which require qualitative answers. Two sample problems taken from a typical set are shown in Figure 5.1. These problems are qualitative restatements of problems from different physics textbooks. The physical situations or surface features in both the qualitative and quantitative versions of all the problems in the set are very different, but all the problems can be represented in the same abstract form (diagram, algebraic symbols, or verbal description using mechanics concepts) and can be solved using the same mechanics principle. Each student produces a solution to each of the problems in the set and then shares with the class the problem analysis, the solution of the problem, and the definitions of technical terms used in the solution or the analysis. This procedure forces students to be explicit about the idiosyncratic meanings

QUANTITATIVE VERSION	QUALITATIVE VERSION
3. Rifle and Bullet Problem A 3-g bullet is fired from a 2.4-kg rifle with a velocity of 360 m/s north. Find the momentum of the bullet and the recoil velocity of the rifle, assuming that no other bodies are involved. (Smith & Cooper, 1979, p. 93)	A bullet is fired from a rifle. Describe the motion of the rifle. How does the velocity of the rifle compare with the velocity of the bullet?
5. Carts and Spring Problem Two heavy frictionless carts are at rest. They are held together by a loop of string. A light spring is compressed between them (see drawing). When the string is burned, the spring expands from 2.0 cm to 3.0 cm, and the carts move apart. Both hit the bumpers fixed to the table at the same instant, but cart A moved 0.45 meter while cart B moved 0.87 meter. What is the ratio of: (a) The speed of A to that of B after the interaction? (b) their masses?  (Haber-Schaim et al., 1976, p. 321)	Two heavy frictionless carts are at rest. They are held together by a loop of string. A light spring is compressed between them. The string is burned and the spring expands. Describe the motion of the carts. How does the velocity of cart A compare with the velocity of cart B?

PHYSICIST'S ANALYSIS



Forces of equal magnitude and opposite in direction are exerted on two unequal masses at rest. How do the velocities of the masses compare? How do the displacements of the masses compare?

FIGURE 5.1 Physics problems with different surface features and the same deep structure.

attributed to technical terms and the principles and propositions that they apply in the analysis of the problem. Each student can contrast his or her analysis of a problem with the analyses presented by other students.

When all of the problems in the set have been considered by the class, the teacher presents the physicists' analysis of the problem by means of diagrams and verbal explanations using the technical vocabulary of mechanics. The expert analysis, based on the common deep structure of all of the problems in the set, is shown in Figure 5.1. The teacher demonstrates that the abstract representation is the same for each of the problems and that the same principle produces a solution to all the problems in the set. Then students analyze their solutions so the problems in light of the physicists' solution and specify how their interpretations differ from that of the physicists.

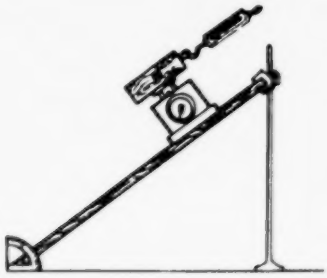
Our illustrative outline of the procedures used in the multiple instances stragegy concerns interactive dialogues about just one set of problems. To be effective in producing the desired change, of course, the strategy must be repeated with other sets of problems with the same deep structure.

Interactive Dialogues using Multiple Representations

The optimal application of this instructional strategy is in situations where the students need to develop understanding of a concept as it applies in a given class of situations. This instructional strategy requires that students work with various representations of the concept, including diagrams, three dimensional manipulative objects, physical models, conventionalized symbols, data tables, and graphs in a way that makes explicit the correspondences among the various representations. We illustrate the strategy by outlining a portion of an instructional sequence. The example involves a 1.0 kg block placed on an inclined plane at various angles (0°–90°) and being held in dynamic equilibrium by a force parallel to the incline (see Figure 5.2). In this situation, three forces are acting on the block—the gravitational force (F_g), the force parallel to the incline (F_t), and the normal reaction force (F_n). One aspect of the importance of this situation in elementary dynamics is that an understanding of the conditions necessary for dynamic equilibrium enables knowledge of the F_n and F_t to be used to establish the magnitudes of the components of F_g parallel and perpendicular to the incline. The multiple representation strategy in which a single physical situation is represented at different levels of abstraction helps force important mental links between the physically relevant information in a physical situation and the latent information in the scientist's abstract representations of the situation.

As shown in Figure 5.2, the physical apparatus to be used in this example consists of a board (the inclined plane), a block (the 1.0 kg object), and two

PHYSICAL SITUATION



SYMBOLIC REPRESENTATIONS

1. Data Table
(numerical and verbal representations)

Angle of incline	45°
Platform scale reading	6.9N
Spring scale reading	6.9N
Weight of block	9.8N

5. Algebraic-Trigonometric Equations
(algebraic and verbal representations)

Angle of incline	θ
Normal reaction force	$F_n = F_g \cos\theta$
Force parallel to incline	$F_l = F_g \sin\theta$
Mass of block	m
Gravitational acceleration	g
Force of gravity on block	$F_g = mg$

2. Vector

3. Parallelogram Vector

4. Right Triangle Vector

FIGURE 5.2 Multiple representations of an equilibrium condition.

spring scales—one a compression spring platform scale to measure the normal reaction force, the other an expansion spring scale to measure the force parallel to the incline. There are six symbolic representations to be coordinated with the physical situation. One is the numerical representation in a

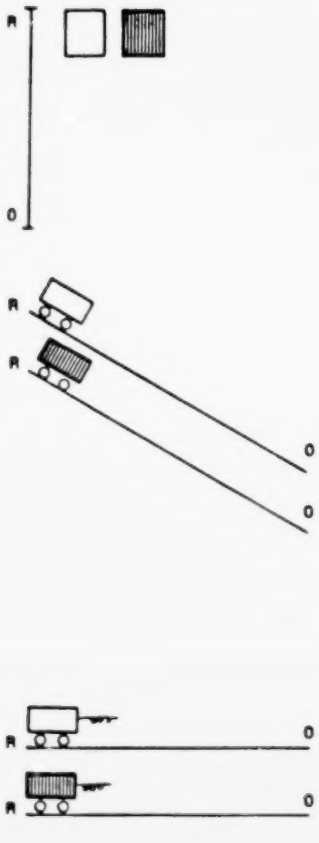
data table, and three more are vector representations. One vector representation shows three forces acting through the block's center of mass. Two others show the vectors rearranged for analysis, one by construction (the parallelogram representation), and the other by the trigonometric relationships of the right triangle. The fifth representation is algebraic-trigonometric and consists of equations for the principal forces in the situation. While all of these representations are equivalent mathematically, conversion from one to the other can be puzzling to the students, who may not recognize the mathematical equivalence. Finally, examples of the sixth symbolic representation are shown with both the numerical representation in the data table and the algebraic-trigonometric representation. Here verbal representation is used to identify measured quantities and the forces acting on the block.

It is by no means a straightforward task for students to coordinate the various symbolic representations with each other and with the physical situation. The instructional strategy aims at mapping the information available in the physical situation onto the symbolic representations and at making the correspondences among the several representations explicit. This is accomplished by having students work simultaneously with two representations and noting how changes in one (for example, an increase in angle of incline and concurrent changes in the two spring scale readings) result in corresponding changes in a symbolic representation (for example, an increase in the angle between F_g and F_n; a lengthening of the vector representing F_t and shortening of the vector representing F_n). Correspondences among the symbolic representations are similarly established by manipulating a variable in one (a change in magnitude of the angle of incline) and mapping the corresponding changes on another symbolic representation or on the physical apparatus.

Ideational Confrontation

The instructional dialogue strategy which we call "ideational confrontation" is designed to help bring about substantial changes in the content of students' motion-of-objects schemata. Certain concepts and propositions in the uninstructed students' schemata must be replaced by or integrated with the concepts and propositions of the physics experts' schemata. We can illustrate this by describing certain specific changes we anticipate in students' motion-of-objects schemata.

Figure 5.3 displays three representative problems which students in an introductory physics course would confront. The first problem is to make a prediction comparing the amount of time required for two blocks of unequal mass to fall a distance of 1 meter. Our hypothesized falling-objects schema



Falling Blocks
The plastic block and the metal block are the same size and shape. Both blocks are held at point R. Then the two blocks are released at the same time and they fall the 1 meter distance to the floor. Compare the time for the plastic block to reach point 0 with the time for the metal block to reach point 0.

Carts on an Incline
The carts are the same size and shape and have the same wheels. One cart is loaded, the other is empty. They are on identical tracks. Starting from rest at R, both carts are released at the same time. Compare the time for the empty cart to reach point 0 with the time for the loaded cart to reach point 0.

Pulled Carts
The carts are the same size and shape and have the same wheels. One cart is loaded, the other is empty. They are on identical tracks. Starting from rest at R, both carts are pulled along the tracks so that the spring on each cart is always extended the same amount. Compare the time for the empty cart to reach point 0 with the time for the loaded cart to reach point 0.

FIGURE 5.3 Three representative introductory physics problems.

for a typical uninstructed student includes the following features. Considering first the object category, the schema contains objects together with their observable physical properties, such as size, shape, and weight. Among the physics concepts in the schema are the object's properties, including volume, mass, and weight, though these concepts are not precisely defined and are poorly differentiated; the objects' average speed in falling and the instantaneous speed at any point (two poorly differentiated concepts); the time elapsed during the fall; and a downward pull on the objects due to the pull, or force, of gravity. Here also is the concept, heavier than, in the sense of greater weight, and the specific application of this concept to the equal-sized

objects of different materials with the result that the metal block is conceived to be heavier than the plastic block. Relevant to this conception is the general rule, stored among the schema's experience-derived propositions, that "Heavier objects fall faster than lighter objects." The uninstructed student applies what he or she believes to be the relevant general rule to the specific physical situation to deduce an answer for the problem. For the situation of the two blocks, the reasoning is: (1) The metal block is heavier than the plastic block. (2) Heavier objects fall faster than lighter objects. (3) Hence, the metal block falls faster than the plastic block. (4) The metal block takes less time to reach point 0 than the plastic block. The form of reasoning leading to the problem's solution is the same, of course, if the relevant general rule selected from the schema's stored propositions is: "According to Galileo, all objects fall at the same speed regardless of their weight." However, the answer to the problem now is that the metal and plastic blocks reach point 0 at the same time.

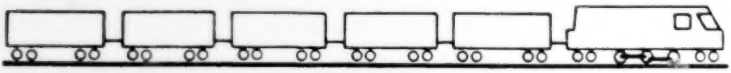
To transform the hypothesized schema of the uninstructed student into a schema approximating an expert's schema requires changes such as the following. With regard to concepts in the schema, in place of concepts which are vaguely defined and poorly differentiated, the transformed schema's concepts have precise qualitative definitions which distinguish them one from the other. For instance, the concepts of *volume*, *mass*, and *weight* are differentiated from one another, and the definitions of *mass* and *weight* incorporate the relationships of these concepts to each other and to major physical principles. In a similar position in the transformed schema is the concept of *force*, a generalized concept central in several major physical principles that was formerly represented only as a *push* or *pull* concept. With regard to principles in the student's new schema, in place of imprecise, experience-derived rules of limited scope and applicability, the transformed schema is dominated by a major physical law which is abstract and broadly applicable, specifically, Newton's second law of motion. Associated with this law are its conditions of applicability, including that the idealization assumptions of Newtonian mechanics are realized, and that a constant net unbalanced force is acting on the objects of interest, here the plastic and metal blocks. Recognition that Newton's second law is applicable to this situation requires that the student's new schema include appropriate links between the abstractions of Newton's second law (mass, force, and acceleration); the physical objects (plastic and metal blocks, identical in shape and volume but differing in mass) and states specified by the problem (initial and final position, initial velocity is zero); and physical constructs not specifically mentioned or observed (force of gravity, acceleration, air resistance). These abstractions or second-order features have no parallel in the student's initial schema and must be abstracted from the physical situation and the real

Original Problem

"9. A freight engine of mass 20,000 kg accelerates from rest up to a velocity of 2.0 m/sec. in 5.0 sec. If it is pulling a train of 20 cars, each with a mass of 10,000 kg, what is the force in the coupling between the engine and the first car?"

(Stollberg & Hill, 1964, p. 49)

Problem Restated in Qualitative Form



A freight train is stationary. It then accelerates away from rest. While the train is accelerating, how does the force exerted by the engine to accelerate the train compare with the force in the coupling between the engine and the first car?

Subsidiary questions: (i) **What assumptions did you make to arrive at your answer?**
(ii) **What principles of physics/laws of motion did you apply to the situation in coming to your answer?**

Knowledge/skills assumed in following outline of Instructional Dialogue strategies:

1. It is assumed that students
   (a) have completed a study of kinematics and Newton's Laws
   (b) are aware that the extension of a rubber band or spring is a reasonable indicator of the magnitude of the extending forces acting on the rubber band or spring
2. It is also assumed that there is instructional value in students having both visual and touch inputs of estimations of the magnitude of forces.

Strategy A Outline of strategy to be used for responses to the qualitative problem of the form "don't know" or "the same."

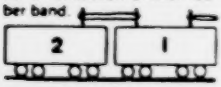
Steps in the Strategy	Purpose of Steps	Commentary on Steps [1]
A1. Have the student pull, using a rubber band, laboratory trolleys (PSSC) carrying various numbers of bricks.	To draw attention to, or re-establish, the qualitative relationship between mass, motion of the mass, and applied force.	Direct observation. Questions to assist processing of the observations would follow, for example, Collins (1977) Rule 1: Ask about a known case, and Rule 11: Specify how the variable depends on a given factor. Specific procedural rules will vary between individuals.
A2. Use two trolleys connected by a rubber band arranged so that the trolleys are almost touching when stationary – hence separation of trolleys is an indicator of extension of that rubber band.  **Have the student pull the trolleys by a rubber band attached to cart 1.**	(a) To establish what specific objects each of the two rubberbands is pulling. (b) To direct attention to the qualitative relationship between mass and force required to accelerate that mass.	As for A1 above. Possible procedural rules include Collins (1977) Rules 13: Probe for differences between two cases, and 11 (see above).

FIGURE 5.4 The freight train problem.

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A3. Repeat A2 with various masses added to cart 1 and/or cart 2.	See purpose (b) in A2.	See A2 above.
A4. Repeat A2 and A3 using a number of carts.	See purpose (a) & (b) in A2.	See A2 above.
A5. Return to qualitative problem. After successful solution of the problem as asked, use strategy B below, if appropriate.		

Strategy B Outline of strategy to be used for responses to the qualative problem of the form "force exerted by the engine is greater than the force in the coupling" (i.e., correct response to question asked).

Steps in Strategy	Purpose of Steps	Commentary on Steps
B1. Ask student if they can be more precise about the relative magnitudes of the two forces.	To establish that ratio of forces is inverse of ratio of total mass/weight of train to mass/weight of cars pulled by the engine. If this is not forthcoming, go to strategy A, beginning at A2. If some such statement is produced, go to B2.	Collins (1977) Rule 4: Ask for prior factors.
B2. Repeat subsidiary questions (i) and (ii) from the qualititive problem.	To link answers to the subsidiary questions to the specific situations presented – both the experiences with carts and the qualitative problem.	Collins (1977) Rule 2: Ask for any factors. Also, in the exploration of individual responses, one or several applications using other rules may be made.

[1] Note. Collins (1977) proposed a series of procedural rules for this form of instructional dialog, and we comment on particular rules which are pertinent to the several steps in our strategy. The procedural rules were recognized and amplified in Collins & Stevens (1981).

FIGURE 5.4 *(continued)*

objects therein, in order for the student to link the physical situation with the second law. Examples of other second-order features are canonical objects, all of whose mass is concentrated at a single point, and vector representations of forces. Given that these second order features are linked with physical objects, the three "real-world" situations described in the problems in Figure 5.3 can all be represented abstractly as pairs of unequal masses (two blocks, two carts), each under the influence of a constant net force (gravity, extended rubber bands). Assuming the influence of friction is minimal, Newton's second law allows the student to predict constant acceleration for each of the objects and to compare the magnitude of the acceleration

produced by unequal forces on unequal masses in the falling blocks and inclined plane problems and on unequal masses under the influence of equal forces in the pulled carts problem.

Despite the numerous changes in the student's schema that we have surmised, some characteristics of the initial schema need not and should not change. In this category are the schema's representations of the physical objects themselves, their properties, and their described or suggested behavior. These are the representations that are utilized, we believe, to initiate a qualitative analysis of a problem. Hence, they are important in the application of our fourth instructional strategy.

Qualitative Analysis of Problems

When an instructional objective calls for altering the structural organization or integrating the concepts and propositions of a schema, the instructional dialogue strategy of the qualitative analysis of problems can be very useful. In order to explain and illustrate the procedures for the qualitative analysis of problems, we have analyzed a number of prototypical physics problems taken from introductory texts. An example of such an analysis is shown in Figure 5.4. Other examples can be found in Champagne, Klopfer, and Gunstone (1982). The general structure of each analysis is simple. Initially, the standard form of the problem is rewritten in qualitative form, with subsidiary questions asking about limitations of, and physics principles used, in the answer given by the student. Then a realistic minimum state, in terms of relevant prior knowledge and experience is selected, and a strategy for working from the state to a successful solution is proposed. At this stage, when we do not have the insights to be derived from data, it is assumed that other, more developed responses can be accommodated by beginning at a later point in this sample strategy. The strategy has been outlined only. It indicates a series of logical steps. Within each step, the essential concept(s) to be developed and the purpose of the step in terms of the problem solution are indicated. In some cases, a particular instructional methodology to be used for a step is shown, while in the remaining cases, only instructional dialogue is anticipated. For each step, the rationale for the procedure is described, referring to the techniques identified by Collins (1977) and Collins and Stevens (1981) when appropriate. For each of the three examples, a procedure for handling a correct answer to the questions asked so as to develop an approach to solving the problem is also given.

Physics Problems and Numerical Exercises

The development of our ideas concerning the qualitative analysis of physics problems has led us to a simple but, we believe, most important recon-

ceptualization of the nature of physics problems vis-a-vis the structure of standard physics texts and curricula. In what seems an obvious extension of the form of solution strategy experts apply to standard physics problems, we wish to describe qualitative problems of the form given here as "Physics Problems." The solution strategy derived from such a problem can then be applied to a set of exercises of the form currently termed problems. These exercises we wish to describe as "numerical examples." The parallels with mathematics instruction are striking. The normal mode of instruction in math involves the development (or, unfortunately, the provision) of a solution strategy for a particular type of problem, for example, factorization of quadratics. Then students are asked to apply this solution strategy to numerical examples. These numerical examples are labeled by most texts and teachers with a description such as "examples," and "exercises," but are rarely termed "problems."

This reconceptualization has, we believe, considerable instructional significance. Current practices seem to be based on the assumption that, by doing "numerical examples," students will themselves extrapolate solution strategies to "problems." Texts commonly approach the task of elucidating methods for solving standard physics questions by giving "numerical examples" and, starting immediately with an equation, describing the appropriate approach. It is apparently assumed that this approach will be transferred by students to other appropriate "numerical examples," but instructional assistance for this transfer is rarely given. Indeed, as any practitioner of physics teaching can testify, assisting students to make such transfer is extraordinarily difficult. As a consequence, we argue that the methods outlined here are designed to foster the development of problem solutions. We believe that solution of numerical examples is a subsequent and more simple step.

INSTRUCTIONAL ISSUES

Two issues which merit some consideration here arise from the instructional strategies we are advocating. First, our proposed instructional dialogue strategy focused on the qualitative analysis of physics problems that makes use of laboratory equipment in some cases (e.g., Step A2, Strategy A in Figure 5.4). This use of laboratory-type experiences may be questioned since laboratory work has not been shown to produce significant cognitive gains for science students. Hence, it is necessary to discuss the specific conceptual basis for our use of laboratory-type experiences in the instruction. The second instructional issue to be discussed is related to our proposed multiple representations strategy and concerns the proper role of analogies in science instruction.

Role of Laboratory Experiences

Studies of instruction with laboratory work versus instruction without laboratory work have consistently suggested no cognitive advantage for the lab work group exists (see, for example, Bates, 1978, for a review). However, much laboratory work in the sciences, in general and physics, in particular can be characterized as follows: students follow some procedure for the collection of data, which is the primary focus of their activity while involved with the apparatus; results are then analyzed and, in many cases, subsidiary questions answered; the end result is the verification (or "discovery") of some law, relationship, or effect of one variable on another. This mode of laboratory work has most frequently resulted in students concentrating on the procedures for data collection and, overwhelmingly, on obtaining the correct answer. In such circumstances, the apparent failure of laboratory activity to markedly foster conceptual development does not seem surprising.

Gagné and White (1978, p. 214) have argued that laboratory work which is performed with the intent of facilitating understanding and conceptual development will better achieve such purposes if it seeks to generate links between episodes and images (derived from the laboratory work) and propositions and intellectual skills. This is an appealing argument, especially given the extent to which introspection reveals images and episodes in one's own memory which relate to specific facts and principles. However, Atkinson (1980), in comparing chemistry instruction with laboratory work and chemistry instruction with only demonstrations, found that the laboratory work did not appear to assist that group in recalling related subject matter even though this group was somewhat more likely to recall relevant images and episodes. Gunstone (1980), in an investigation of physics learning, found virtually no propositional connections between physics concepts which were derived from laboratory work. Since both of these studies utilized laboratory work in the verification mode described above, it is plausible to suggest that such laboratory work, because of the focus it gives to student activity, is unlikely to generate the links among images, episodes, propositions, and concepts argued by Gagné and White.

In considering the lack of cognitive gain from traditional laboratory work, White (1979) has argued for the inclusion of three types of practical activities not usually found in science courses. One of these activities is used in the strategies for developing problem solutions which are outlined in Figure 5.4. This activity

> is intended to establish generalized episodes involving materials and events of common experience, with the purposes of linking school subject matter and daily life and of providing experiences which will be called into play in making subsequent information comprehensible. (White, 1979, p. 387)

Directed hands-on experience with physical objects is included in our strategies because of the extent to which such experience can relate aspects of the problem to relevant prior experience in the world at large. It can also provide sensory inputs about situations and provide episodes or images as memory structures for later recall. It is of interest to note that this overt attempt to bring to the solution of the problem relevant real-world knowledge is in line with arguments for the importance of such knowledge to the individual's problem solution (see, e.g., Duran, 1980; Neisser, 1976). Others (e.g., West, 1980) have probed students' links between curriculum knowledge and general knowledge as an important dimension of students' cognitive structures.

This rationale for a particular form of laboratory work will be briefly illustrated by reference to the proposed strategy for the freight train problem in Figure 5.5. The use of rubber bands to pull and connect laboratory trolleys illustrates the basic principles underlying the freight train problem. By manipulating masses and the number of trolleys, students will derive *qualitative* relationships between the relevant variables, be assisted to relate these relationships to the underlying physics principles, and, perhaps most importantly, be given a memorial referent to which they may relate this information. In addition, some students will relate this experimental manipulation to previous relevant experience (e.g., pulling peers while skating). Before the event, it is clearly not possible to determine which students have relevant prior experience. Hence, the drawing out and relating of any such experience will be achieved by the instructional strategy to be used.

Seen in this light, the use of the trolleys can be clearly characterized as an attempt to provide a physical analogy to the freight train. Thus, in this instance, an analogy is used as a part of our qualitative analysis of problems strategy. Analogies crop up even more frequently in our proposed instructional strategy of interactive dialogues using multiple representations. For this reason, we need to be aware of the issue of the potential dangers of the use of analogies in instruction.

Analogies in Instruction

The role of analogies and models (which are little more than formalized or institutionalized analogies) in the development of science has been widely discussed by philosophers of science. Further, much has been written about the manner in which analogies can inhibit or distort the development of science when inappropriate deductions are made on the basis of existing analogies (Harré, 1965; Nagel, 1961; Scheffler, 1969). A parallel situation exists in science instruction as Gee (1978) and Weller (1970) have indicated, where the use of analogies can result in students making inappropriate extensions of an analogy to generate false information. White and Gunstone

(1980), in an investigation of cognitive structures associated with electricity, found a clear and extreme example of an inappropriate extension. A college science graduate who had been given the water flow analogy during his early instructional experience with electric current had extended the analogy on his own initiative so as to equate the functions of a pipe in the water analogy and the insulation surrounding a conducting wire. As a consequence, he believed resistance to electric current arose from the friction between electricity and the surrounding insulation and that electrical leakage was akin to a hole in a water pipe and that it could result from a bare electrical conductor. He had deduced that much of the research effort in electrical engineering was devoted to the production of more efficient (i.e., less friction-generating) insulating covers for wires.

On the positive side, Gentner (1980) has sought to frame the issue of how multiple representations may help to develop understanding of science concepts in terms of structural differences between good and poor analogies. Gentner argues that the explanatory power of analogies in learning science concepts rests on the fact that analogies point up equivalent relationships, rather than equivalent objects, within two distinct systems. Gentner develops a set of criteria by which to evaluate the likely effectiveness of particular analogies in explaining science concepts: clarity, a measure of the precision of the mapping; richness, a measure of the sheer number of mappings between two systems; abstractness, a measure of the level of relationships mapped between the systems; and systematicity, a measure of the extent to which the constraints in one system of the analogy are isomorphic to the constraints in the second system.

An important and neglected aspect of the instructional use of analogies is an understanding of the limitations of the analogy. Developing such understanding also adds to the understanding of the science concept which the analogy is used to illustrate. Consequently, we are explicit about significant limitations to be developed with students when using analogies in providing experiences with the multiple representations of a concept.

SOME ASPECTS OF PROPOSED RESEARCH

The foregoing sections of this chapter have explicated an alternative approach to conceptualizing the well-known instructional problem of the difficulty that beginning physics students experience in learning mechanics. We have sought to identify and characterize the entering students' alternative conceptions of motion that contravene the physicists' declarative knowledge about motion, the knowledge whose contents and structure are desired outcomes of mechanics instruction. Finally, taking seriously the students'

alternative conceptions, we have argued the necessity of deliberately altering the students' declarative knowledge to align it with that of the physicists', and we have suggested several dialogue-based instructional strategies for effecting these changes. However, we are not content with proposing a new approach, no matter how logical or how well supported by research it might be. We intend to investigate the strategies and issues which have been argued above. The major hypothesis to be tested in our proposed research is that engaging beginning physics students in instructional dialogues that utilize one or more of our proposed instructional strategies will produce changes in the students' declarative knowledge about the motion-of-objects. Our further hypothesis is that, after completion of the specified instruction, the students' schemata will have several significant features which are characteristic of the declarative knowledge of physics experts.

Our first task in this research is to specify the scope and sequence of questions and manipulative experiences which will serve as the stimuli for the instructional dialogues. We have illustrated the rationales for the construction of stimulus materials in conjunction with the example exhibited in Figure 5.4. From analyses similar to these, for every strategy we select for the instruction, we can derive specifications for the issues which need to be raised, the topics which will be discussed in the dialogues, and the laboratory-type experiences which are required to provide essential observations or episodes. With the instructional strategies and the content of the instruction specified, the final design task is to incorporate these into instructional materials.

For the multiple instances strategy, for example, we plan to select problems that form a sequence in which the problems, though differing in surface features, can all be solved by making essentially the same qualitative analysis and by utilizing the same physical principle. The three physics problems shown in Figure 5.3 exemplify this kind of sequence. There will be several such sequences in the instruction, whose scope is an introduction to dynamics under the purview of Newton's laws of motion. The specific problem sequences to be included in the instruction will be determined by our analyses of which topics are necessary to induce changes in students' schemata and by determining how far along the continuum of approximating the physics experts' schemata we wish the students to proceed.

For assessing the students' motion-of-objects schemata before and after instruction, we shall use several different techniques drawn from our own and other researchers' studies. Each technique probes students' declarative knowledge in a somewhat different fashion, yielding unique shards of data for analysis. By combining the results of the analyses of the data from several sources, we should obtain rather complete descriptions of the contents and structure of students' schemata. The assessment techniques we plan to use

include DOE tasks, which we have used in previous studies (e.g., Champagne, Klopfer, & Anderson, 1980; Champagne, Klopfer, Solomon, & Cahn, 1980), and the interview-about-instances technique (Osborne & Gilbert, 1980).

Asking subjects to sort physics problems into types according to their own criteria and obtaining think-aloud protocols as subjects solve problems are two techniques used to study the representation of physics problems by experts and novices (Chi et al., 1981). We shall apply these techniques in our student assessments, except we shall restrict the domain to the qualitative mechanics problems in which we are interested. From analyses of the students' performances and explanations, we shall learn whether the students attend to surface features or to second-order features in analyzing problems, and we shall be able to infer whether the students' schemata are oriented by the objects of the problem or by a physical principle. To monitor the students' schema changes as they engage in instructional dialogues, techniques of protocol analysis, as suggested for example, by Ericksson & Simon (1980), will be applied. This research will provide significant empirical tests of the proposed instructional strategies and the psychological theory on which they are based.

REFERENCES

Anderson, J. (1983). *Architecture of cognition*. Cambridge, MA: Harvard University Press.

Anderson, R. C. (1977). The notion of schemata and the educational enterprise: General discussion of the conference. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge*. Hillsdale, NJ: Erlbaum.

Anderson, R. C., Reynolds, R. E., Schallert, D. L., & Goetz, E. T. (1977). Frameworks for comprehending discourse. *American Educational Research Journal, 14*, 367–381.

Arons, A. B. (1976). Cultivating the capacity for formal reasoning: Objectives and procedures in an introductory physical science course. *American Journal of Physics, 44*(9), 834–838.

Atkinson, E. P. (1980). *Instruction-memory-performance*. Unpublished doctoral dissertation, Monash University, Melbourne, Australia.

Bates, G. (1978). The role of the laboratory in secondary school science programs. In M. B. Rowe (Ed.), *What research says to the science teacher*. Washington, DC: National Science Teachers Association.

Bransford, J. D., & McCarrell, N. S. (1974). A sketch of a cognitive approach to comprehension. In W. B. Weimer and D. S. Palermo (Eds.), *Cognition and the symbolic processes*. Hillsdale, NJ: Erlbaum.

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1982, May). *A perspective on the differences between expert and novice performance in solving physics problems*. Paper given at the annual meeting of the Australian Science Education Research Association, Sydney.

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics, 48*, 1074–1079.

Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. *Educational Psychologist, 17*, 31–53.

Champagne, A. B., Klopfer, L. E., Solomon, C. A., & Cahn, A. D. (1980). *Interactions of students' knowledge with their comprehension and design of science experiments*. University of Pittsburgh, Learning Research and Development Center Publication Series, 1980/9. (ERIC Document Reproduction Service No. ED 188 950)

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121–152.

Collins, A. (1977). Processes in acquiring knowledge. In R. C. Anderson, R. J. Spiro, & W. C. Montague (Eds.), *Schooling and the acquisition of knowledge*. Hillsdale, NJ: Erlbaum.

Collins, A., & Stevens, A. L. (1981). Goals and strategies of inquiry teachers. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. II). Hillsdale, NJ: Erlbaum.

Dijksterhuis, E. J. (1969). *The mechanization of the world picture*. London: Oxford University Press.

Driver, R. (1973). *The representation of conceptual frameworks in young adolescent science students*. Unpublished doctoral dissertation, University of Illinois.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*, 61–84.

Duran, R. P. (1980, October). *Influences of practical and instrumental knowledge on problem solving*. Paper presented at the NIE–LRDC Conference on Thinking and Learning Skills, Pittsburgh, PA.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review, 87*, 215–251.

Gagné, R. M., & White, R. T. (1978). Memory structures and learning outcome. *Review of Educational Research, 48*, 187–222.

Gee, B. (1978). Models as a pedagogical tool: Can we learn from Maxwell? *Physics Education, 13*, 287–291.

Gentner, D. (1980). *The structure of analogical models in science* (BBN Report No. 4451). Cambridge, MA: Bolt, Beranek & Newman.

Gerson, R., & Primrose, R. (1977). Results of a remedial laboratory program based on a Piaget model for engineering and science freshmen. *American Journal of Physics, 45*, 649–651.

Gunstone, R. F. (1980). *Structural outcomes of physics instruction*. Unpublished doctoral dissertation, Monash University, Melbourne, Australia.

Gunstone, R. F., & White, R. T. (1981). Understanding of gravity. *Science Education, 65*, 291–300.

Halley, J. W., & Eaton, B. (1975). A course in physics of human motion. *American Journal of Physics, 43*, 1007–1010.

Harre, R. (1965). *An introduction to the logic of the sciences*. London: Macmillan.

Hudson, H. T., & McIntire, W. R. (1977). Correlation between mathematical skills and the success of physics. *American Journal of Physics, 45*, 470–471.

Kolody, G. O. (1977). How students learn velocity and acceleration. *Journal of College Science Teaching, 6*, 224–227.

Leboutet-Barrell, L. (1976). Concepts of mechanics in young people. *Physics Education, 11*, 462–466.

Lindsay, P. H., & Norman, D. (1972). *An introduction to psychology*. New York: Academic Press.

Mallinson, G. G. (1977). Summary of research in science education–1975. *Science Education*, special issue.

Nagel, E. (1961). *The structure of science: Problems in the logic of scientific explanation*. London: Routledge & Kegan Paul.

Neisser, U. (1976). General, academic, and artificial intelligence. In L. B. Resnick (Ed.), *The nature of intelligence*. Hillsdale, NJ: Erlbaum.

Osborne, R. J., & Gilbert, J. K. (1980). A technique for exploring students' views of the world. *Physics Education, 15*, 376–379.

Peterson, K. D. (1979). The albertus magnus lyceum: A thomistic approach to science education. *Dissertation Abstracts International*, *38*(1), 151–A.

Renner, J. W., Grant, R. M., & Sutherland, J. (1978). Content and concrete thought. *Science Education, 62*, 215–221.

Scheffler, I. (1969). *The anatomy of inquiry: Philosophical studies in the theory of science*. New York: Knopf.

Singer, B., & Benassi, V. A. (1981). Occult beliefs. Media distortions, social uncertainty, and deficiencies of human reasoning seem to be at the basis of occult beliefs. *American Scientist, 69*, 49–55.

Weller, C. M. (1970). The role of analogy in teaching science. *Journal of Research in Science Teaching, 7*, 113–119.

West, L. H. T. (1980). Towards descriptions of the cognitive structures of science students. In W. F. Archenhold, R. H. Driver, A. Orton, & C. Wood-Robinson (Eds.), *Cognitive development research in science and mathematics*. Leeds: University of Leeds.

White, R. T. (1979). Relevance of practical work to comprehension of physics. *Physics Education, 14*, 384–387.

White, R. T., & Gunstone, R. F. (1980, November). *Converting memory protocols to scores on several dimensions*. Paper presented at the annual meeting of the Australian Association for Research in Education, Sydney, Australia.